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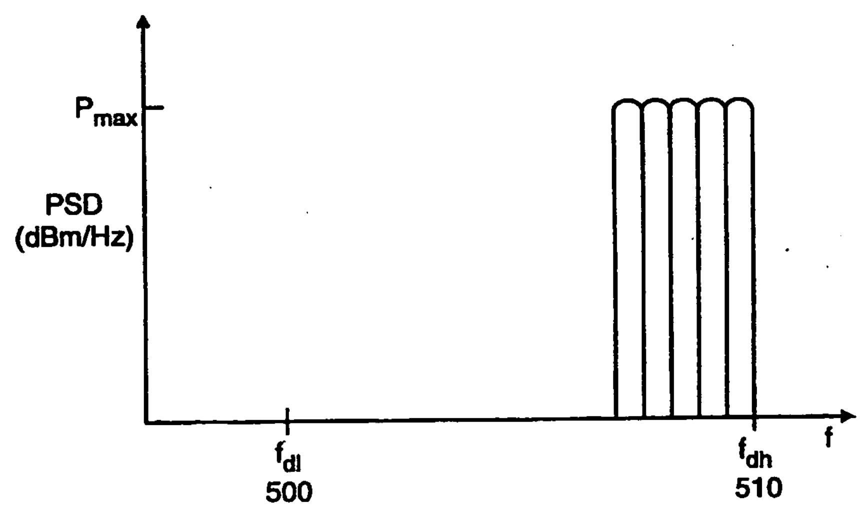

(57) Abstract

A method and apparatus for reducing the strength of interference (e.g., crosstalk noise and/or echo interference) in multicarrier communications. Carrier subchannels are selected from a plurality of carriers having a range of frequencies. The carrier subchannels are selected by first selecting a first subset of the plurality of carriers, spanning a frequency range having a highest frequency end and a lowest frequency end. Each subchannel in the subset can carry a signal of at least one bit. At least one of the carrier subchannels of the subset for transmitting one or more bits of the digital signals is allocated at one of the ends of the frequency range. Input digital signals are modulated on to the carrier subchannels, ~~are transmitted and received and~~ are demodulated as output digital signals. Carrier subchannels are used in such a way as to reduce or minimize the magnitude of interference phenomena, including near end crosstalk, far end crosstalk, echo, and noise, when transmitting digital signals.

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APPARATUS AND METHOD OF TONE ALLOCATION IN DIGITAL SUBSCRIBER LINE SYSTEMS

CROSS REFERENCE TO RELATED APPLICATION

This application claims the benefit of and priority to copending U.S. provisional patent application Serial No. 60/121,194 filed February 23, 1999, entitled "Method of Tone Allocation In Digital Subscriber Line Systems," the entirety of which provisional application is incorporated herein by reference.

FIELD OF THE INVENTION

The invention relates to communication systems and, more particularly, to the transmission of information using multicarrier transmission techniques.

BRIEF DISCUSSION OF BACKGROUND INFORMATION

Telephone companies have found that the large embedded base of twisted wire pairs which are presently used for analog telephone services can also be used to deliver high speed digital signals to subscribers. Digital signals can be used to provide data services including high-speed Internet access, video programming, and traditional telephony services.

The techniques used to transmit digital signals over twisted wire pairs include Asymmetric Digital Subscriber Line (ADSL), High-bit rate Digital Subscriber Line (HDSL), Rate Adaptive Digital Subscriber Line (RADSL), and Very high speed Digital Subscriber Line (VDSL). These techniques are generally referred to as xDSL or DSL transmission techniques.

Modems for use with xDSL transmission techniques have been developed that transmit information in a number of small frequency bins referred to as tones or carrier subchannels. The carrier subchannels are separated from each other in frequency by a relatively small amount, e.g.,

the frequency spacing between tones is 4.3125 kHz, with a tolerance of +/- 50 ppm. The carrier subchannels collectively form what is effectively a broad bandwidth communications channel. Multicarrier systems have the advantage that they can vary the amount of information carried in each tone and place a payload in each tone which is consistent with the signal-to-noise ratio (SNR) which can be obtained in that tone or carrier subchannel.

Single carrier systems have also been utilized to provide data communications over twisted wire pairs. Although single carrier systems are distinguished from multicarrier systems in that they do not use closely spaced tones to transport data, many single carrier systems utilize more than one carrier in either the downstream direction (central office to subscriber), the upstream direction (subscriber to central office) or both directions. When used herein, the term tone (or carrier subchannel) refers both to the closely spaced tones within multicarrier systems, as well as the wide tones that are formed from modulated single carriers.

Present multicarrier systems, or systems utilizing a plurality of carrier subchannels, maximize the SNR margin in each tone or carrier subchannel by using as many tones as can be used for the service and transmitting at the maximum allowable power on each tone or carrier subchannel. As a result, if the payload is small, a large number of tones may be used at a power that is higher than what is really required to transmit the payload at an acceptable quality. This leads to excess power in a group of twisted wire pairs and can ultimately decrease the total capacity of the group.

The maximum amount of information that can be encoded onto a particular carrier subchannel is a function of the SNR of the communication channel with respect to that carrier subchannel. The SNR of a communication channel can vary with frequency so that the maximum amount of information that can be encoded onto a carrier subchannel may have frequency dependence.

One concern with xDSL systems is crosstalk, or a form of electromagnetic interference that occurs between twisted wire pairs carrying signals to different locations. Crosstalk arises from the coupling of signals from one twisted wire pair into another twisted wire pair along the transmission path. This form of interference, which is observed as the reception of signals intended for one modem at another unintended recipient modem, can limit the capacity of the xDSL system, and in some circumstances may render a twisted wire pair unusable for any type of xDSL service.

In addition to the problem of utilizing more tones or carrier subchannels than are necessary to carry a given payload, and crosstalk problems, xDSL systems are subject to the "near-far" problem. This problem occurs when a modem in a telephone central office transmits a signal over a relatively long distance to a home in a serving area while a second modem, located closer to the home, transmits a signal over a second twisted wire pair in the same group of twisted pairs, known as a binder group. If both modems transmit at the maximum allowed power level (e.g., in the range of –38 to -40 dBm/Hz) over the allowed frequency band, the signal on the second modem (closer to the residence) is much higher than is actually required to maintain an acceptable SNR. The excessive power can cause significant crosstalk on the first twisted wire pair or on other twisted wire pairs in the binder group.

Other forms of interference that can degrade the quality of service in a multiple twisted pair binder include echo and noise. Echo is the observation of reflections from signals that are transmitted along a twisted pair, and can be caused by such a transmitted signal encountering impedance mismatches or improper terminations of the transmission line. In particular, echo is an interference that has its root cause in a transmission by the transmitter section of a transceiver that results in reception of a spurious signal by the receiver section of the same transceiver. Noise is the observation of apparently random signals, and can be caused by natural phenomena

such as lightning or by man-made switching phenomena such as the radiated signals from switching power supplies and the like.

SUMMARY OF THE INVENTION

Thus, it is an object of the present invention to provide a multicarrier communication system having reduced or minimized interference in a multicarrier communication system.

It is another object of the invention to provide a method that allocates tones or carrier subchannels for transmitting digital signals at such frequencies and at such power that the overall transmission capacity of a group of twisted wire pairs is optimized.

In one aspect the invention features a multicarrier data modulation method for reducing the effect of interference phenomena in a communications system having a plurality of transceivers. A plurality of carrier subchannels are provided for use in modulating digital signals of an input data stream. For the carrier subchannels, a subset spanning a range of frequencies having a highest frequency end and a lowest frequency end is determined. Each carrier subchannel of the subset is capable of carrying at least one bit of the digital signals. At least one of the carrier subchannels of the subset is allocated for transmitting one or more bits of the digital signals. Every allocated carrier subchannel of the subset is at one of the ends of the frequency range so as to reduce the effect of an interference phenomenon .

In one embodiment, at least one carrier subchannel in the subset carries fewer bits than that carrier subchannel is capable of carrying. In another embodiment of the invention, the allocating of the carrier subchannels uses fewer than all of the carrier subchannels in the subset. In yet another embodiment, the range of frequencies in the subset of carrier subchannels includes at least one carrier subchannel that is incapable of carrying at least one bit. In still another embodiment, digital signals communicated from a first transceiver to a second transceiver are modulated with a first range of frequencies, the first range of frequencies allocated from a first subset of the plurality of carrier subchannels, and digital signals communicated from the second

transceiver to the first transceiver are modulated using a second range of frequencies, the second range of frequencies allocated from a second subset of the plurality of carrier subchannels different from the first subset of the plurality of carrier subchannels.

In another embodiment, a gain of at least one carrier subchannel in the subset is adjusted to reduce the number of bits that the carrier subchannel can carry from a maximum number of bits to a lesser number of bits that is sufficient to carry the information present in a digital signal. In one embodiment, the interference phenomenon is at least one of near end crosstalk, far end crosstalk, noise, and echo.

In another embodiment, a maximum number of bits of a digital signal that each carrier subchannel of the subset can carry is determined to provide a predetermined quality of service. In still another embodiment, the predetermined quality of service is determined using at least one of a bit transmission rate, a bit error rate, a signal-to-noise ratio margin, and a power.

In these embodiments higher frequency tones or carrier subchannels are selected on short loops, where such tones or carrier subchannels will provide an adequate SNR. Low frequency tones or carrier subchannels will tend to be utilized in long loops, where the SNR for the higher frequency tones or carrier subchannels is not sufficient to maintain an acceptable bit error ratio.

One advantage of these embodiments is that far end crosstalk is decreased in one or both directions. Another advantage of these embodiments is that they maintain the maximum spectral separation from the downstream and upstream bands. An advantage of these embodiments is that they decrease the near end crosstalk in one or both directions. Since near end crosstalk is caused by the upstream signals within a binder interfering with downstream signals and vice-versa, increasing the frequency spacing between upstream and downstream bands will decrease near end crosstalk effects.

Still another advantage of these embodiments is that the interference cause by echo can be reduced. By maximally separating the upstream band from the downstream band echo effects

within a transceiver. which are the reception of the transceiver's own transmitted signal at the transceiver's receiver. are decreased. The receiver does not detect echo even if it is present. because the receiver is not sensitive at the frequencies that correspond to the transmitted signal that is being directed back as an echo. This is accomplished by the fact that the increased frequency separation between the transmitted signal and the received signal permit more effective filtering of reflected signals.

Another feature of the present invention is the ability to control tone power to prevent an excess of power from being utilized. The use of excess power has the additional result of decreasing the overall capacity of a group of twisted wire pairs. This feature is realized by determining the SNR at each tone and insuring that the payload is increased until the SNR is such that there is an acceptable, but not excessive, margin. In this way each tone transmits a power level which supports the maximum data rate with an acceptable margin. For data rates which do not require use of all of the tones or carrier subchannels, lower tones or carrier subchannels remain unused and thus reduce the overall emitted power and interference generated by that modem.

An advantage of the present invention is that it provides a system that can allocate tones or carrier subchannels, and can reduce crosstalk within a binder group.

In another aspect of the invention, a multicarrier data modulation apparatus reduces the effect of interference phenomena in a communications system that includes a plurality of transceivers communicating with each other. A module modulates digital signals of an input data stream on to a plurality of carrier subchannels. A subchannel selection module selects a subset of the plurality of carrier subchannels. The subset spans a range of frequencies having a highest frequency end and a lowest frequency end. Each carrier subchannel of the subset can carry at least one bit of the digital signals. A carrier subchannel allocation module allocates at least one of the carrier subchannels of the subset for transmitting one or more bits of the digital signals.

Every allocated carrier subchannel of the subset is at one of the ends of the frequency range so as to reduce the effect of an interference phenomenon.

In one embodiment, the digital signal modulation module uses fewer than all of the carrier subchannels in the subset. In another embodiment, the subset of carrier subchannels spans a range of frequencies that includes at least one carrier subchannel that is incapable of carrying at least one bit. In yet another embodiment, the apparatus further comprises a module that receives a transmitted digital signal that has been modulated on to one or more carrier subchannels. In one embodiment, transmitted digital signals are modulated with a first range of frequencies, the first range of frequencies allocated from a first subset of the plurality of carrier subchannels, and received digital signals are modulated with a second range of frequencies, the second range of frequencies allocated from a second subset of the plurality of carrier subchannels different from the first subset of the plurality of carrier subchannels.

In another embodiment, the apparatus further comprises a gain control module that controls a gain of at least one carrier subchannel in the subset to reduce a number of bits that the carrier subchannel can carry from a maximum number of bits to a lesser number of bits sufficient to carry the information present in a digital signal. In yet another embodiment, the gain control module controls the gain such that the lesser number of bits is a minimum number of bits necessary to carry the information present in the digital signal.

In still another embodiment, the apparatus further comprises an interference detection module that determines a maximum number of bits of a digital signal that each carrier subchannel of the subset can carry to provide a predetermined quality of service. In another embodiment, the interference detection module detects a parameter selected from the group of parameters consisting of a bit transmission rate, a bit error rate, a signal-to-noise ratio, a power, a near end crosstalk, a far end crosstalk, a noise level, and an echo.

In another aspect, the invention involves a multicarrier data modulation apparatus that reduces the effect of interference phenomenon a communication system that uses a plurality of transceivers communicating with each other. The apparatus comprises a module that receives a transmitted digital signal that has been modulated on to one or more carrier subchannels, the one or more carrier subchannels comprising a subset of carrier subchannels allocated from a plurality of carrier subchannels, the subset spanning a range of frequencies having a highest frequency end and a lowest frequency end, at least one of the carrier subchannels of the subset being capable of carrying at least one bit of the digital signals, wherein every allocated carrier subchannel of the subset is at one of the ends of the frequency range so as to reduce the effect of an interference phenomenon. The apparatus also comprises a demodulator module that demodulates the transmitted digital signal that has been modulated on to one or more carrier subchannels, and that creates from the demodulated transmitted digital signal an output data stream.

In another aspect, the invention features a computer program recorded on a machine-readable medium. When the computer program executes on a computer, the program performs the step of determining a subset of a plurality of carrier subchannels, the subset spanning a range of frequencies having a highest frequency end and a lowest frequency end, each carrier subchannel of the subset being capable of carrying at least one bit of the digital signals. The computer program when executing on a computer also performs the step of allocating at least one of the carrier subchannels of the subset for transmitting one or more bits of the digital signals, every allocated carrier subchannel of the subset being at one of the ends of the frequency range so as to reduce the effect of an interference phenomenon.

In one embodiment, the computer program, when executing on a computer, also performs the step of determining a maximum number of bits of a digital signal that a carrier subchannel can carry to provide a predetermined quality of service. In another embodiment, the computer

program, when executing on a computer, also performs the step of modulating the digital signal with a first carrier subchannel having a first frequency using the maximum number of bits that the first carrier subchannel can carry before modulating the digital signal with a second carrier subchannel having a second frequency. In still another embodiment, the computer program, when executing on a computer, also performs the steps of calculating a reduced number of bits that the carrier subchannel carries from the maximum number of bits that the carrier subchannel can carry to a lesser number of bits sufficient to carry the information present in a digital signal that is to be transmitted, and modulating the digital signal with the carrier subchannel using the lesser number of bits in place of the maximum number of bits.

The invention can be applied in circumstances when a single network operator has control over the binder group, or when multiple network operators are utilizing twisted wire pairs within a binder. In the case of multiple operators that use twisted wire pairs within a binder use of the present invention allows the overall throughput of the binder to be higher than would be the case if either one of the network operators use a payload/power allocation scheme in which signal to noise margin is maximized using as many tones or carrier subchannels as possible.

The invention can also be applied in circumstances in which subscribers are located at varying distances from the source of the ADSL signal. The present invention helps alleviate the "near-far" problem in which excessively high-power signals used for subscribers that are close to a transmitter cause high levels of crosstalk on lines that connect subscribers that are far from the signal source.

According to the present invention. a multicarrier communication technique is provided wherein bit loading is carried out in such a way as to reduce or minimize the magnitude of interference phenomena (e.g., crosstalk, echo. and noise interference).

These and other features and advantages of the present invention will become apparent upon reference to the following Description and Drawings, wherein like numerals depict like parts, and in which:

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1A, 1B, 1C and 1D illustrate various exemplary configurations for a digital subscriber line system;

FIG. 2A illustrates the problem of crosstalk in an xDSL system;

FIG. 2B illustrates an embodiment of a binder group;

FIG. 3 illustrates a diagram for an embodiment of a spectrum management system;

FIG. 4 illustrates a computer on which an embodiment of the present invention can be implemented;

FIGS. 5A and 5B illustrate an embodiment of tone or carrier subchannel allocation in traditional multicarrier DSL systems;

FIGS. 6A, 6B, 6C and 6D illustrate tone or carrier subchannel allocation in accordance with the principles of the invention;

FIGS. 7A, 7B, 7C and 7D illustrate tone or carrier subchannel power control in accordance with the principles of the invention;

FIGS. 8A and 8B illustrate an exemplary flowchart for tone or carrier subchannel allocation according to the invention; and

FIG. 9 illustrates an exemplary flowchart for tone or carrier subchannel allocation and power control according to the invention.

DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

FIG. 1A illustrates an embodiment of a system for the transmission of services using xDSL modems. A first modem channel bank 100 houses a first central office side xDSL modem (referred to herein as ATU-C1) 110 which is connected to a first twisted wire pair 140. The first

twisted wire pair 140 is part of a binder group 130. The first central office side xDSL modem 110 delivers an xDSL signal to a first subscriber side xDSL modem (referred to herein as ATU-R1) 160 which is present in a first residence 150.

As shown in FIG. 1A, a second central office side xDSL modem (ATU-C2) 115 resident in the first modem channel bank 100 delivers signals over twisted wire pair 142, which is part of the binder group 130. ATU-C2 115 delivers an xDSL signal to a second subscriber side modem (ATU-R2) 165 that is present in a second residence 152. ATU-R1 160 or ATU-R2 165 may be in a business, apartment building, or other subscriber location. FIG. 1A represents a configuration in which the first central office side xDSL modem 110 and the second office side xDSL modem 115 are located in a single channel bank, and where the subscribers are located at varying distances from the central office. As an example, the first residence 150 may be only several hundred feet from the central office, while the second residence 152 may be as far as 20,000 feet from the central office.

As shown in FIG. 1A, a computer 120 is used to monitor the first modem channel bank 100. In one embodiment, the tone or carrier subchannel allocation system resides on computer 120. In another embodiment, the tone or carrier subchannel allocation system resides on a microprocessor or Application Specific Integrated Circuit (ASIC) which is part of the xDSL modem. The tone or carrier subchannel allocation system can be realized on a single processor, either in computer 120 or in the xDSL modem, or can be realized in a distributed configuration in which multiple computers are used to perform tone or carrier subchannel payload allocation and tone or carrier subchannel power control. The modules that comprise the tone or carrier subchannel allocation system can be implemented in hardware, or can be implemented in a combination of hardware and software.

FIG. 1B represents a configuration in which a second modem channel bank 105 is present and is used to house the second central office side xDSL modem (ATU-C2) 115. This

configuration is typical when a Competitive Local Exchange Carrier (CLEC) obtains access to a group of twisted wire pairs from an Incumbent Local Exchange Carrier (ILEC), including the second twisted wire pair 142. Both the first twisted wire pair 140 and the second twisted wire pair 142 can form part of the binder group 130. As shown in FIG. 1B, a second computer 122 can be used to control the second modem channel bank 105. The tone or carrier subchannel allocation system can be present on the second computer 122, in the modems in the second channel bank 105, or distributed between the various processors in the system. Once again, the modules that comprise both of the tone or carrier subchannel allocation systems can be implemented in hardware, or can be implemented in a combination of hardware and software.

FIG. 1C represents a configuration in which optical fiber is used to transport signals to remote locations in the access area where xDSL modems are used to transmit and receive data over twisted wire pair connections to the residences. As shown in FIG. 1C, a Host Digital Terminal (HDT) 101 houses the first central office side modem 110 which connects to the first subscriber side modem 160 in the first residence 150 over the first twisted wire pair 140. HDT 101 also houses a first fiber optic transceiver 118 which connects to a first optical fiber 125, further connected to a cabinet 135. Cabinet 135 houses a first remotely located xDSL modem 115 that connects to the second subscriber side xDSL modem 165 in the second residence 152. HDT 101 can also house a second fiber optic transceiver 121 that is connected to a node 138 via a second optical fiber 127. Node 138 houses a second remotely located xDSL modem 122 that connects via twisted wire pair 143 to a third subscriber side xDSL modem 167 in a third residence 155.

As illustrated in FIG. 1C, twisted wire pairs 140, 142, and 143 can all form part of the binder group 130. FIG. 1C represents the situation in which optical fiber is used to support remotely located equipment, and as a result there may be significant variations in the lengths of twisted wire pairs that connect the xDSL modems. Once again, the modules that comprise any of

the tone or carrier subchannel allocation systems can be implemented in hardware, or can be implemented in a combination of hardware and software.

FIG. 1D is another exemplary configuration, which, although depicting only one twisted wire pair 171, should be understood to represent a system and method in which many twisted wire pairs simultaneously connect the telephone central office 170 to a plurality of subscribers. System 185 includes both the telephone central office 170 and a subscriber premises 190. The telephone central office 170 is connected to a remote subscriber by a twisted pair subscriber line 171. The central office is also connected to a digital data network 180 via a digital subscriber line access multiplexer ("DSLAM") 178 or alternatively, via a data enabled switch line card, for sending and receiving digital data. The central office 170 is also connected through a local switch bank 172 to a public switched telephone network (PSTN) 182 for sending and receiving voice and other low frequency communications. The DSLAM 178 connects to a "plain old telephone service" ("POTS") splitter 174 through an ADSL transceiver unit 176. The ADSL transceiver unit 176 can be a line card. The local switch 172 also connects to the splitter 174. The splitter 174separates data and voice signals received from the twisted pair line 171.

At the subscriber premises 190 end of the twisted pair line 171, a splitter192 passes the POTS signals from the twisted pair line 171to devices such as telephone handsets 189, 199, and passes the digital data signals to a subscriber ADSL transceiver unit194 for use in devices such as a personal computer 196 that use digital data. The ADSL transceiver unit 194 can be incorporated as a card in the personal computer 196 or as a stand-alone device that attaches to a computer port or connector of the personal computer 196.

FIG. 2A illustrates the phenomena of crosstalk between the first twisted wire pair 140 and the second twisted wire pair 142. A first signal transmitted from ATU-C1 110 travelling down the first twisted wire pair 140 can be electromagnetically coupled to the second twisted wire pair 142. Similarly, a second signal travelling down the first twisted wire pair 142 can be

electromagnetically coupled to the second twisted wire pair 140. Either situation can result in crosstalk. As shown in FIG. 2A. two types of crosstalk can result. including Near-End Crosstalk (NEXT) 210, and Far-End Crosstalk (FEXT) 220.

Consider the connection carried by twisted wire pair 140. NEXT 210 is the coupling of the transmitted signal on the second twisted wire pair 142 to the first twisted wire pair 140, where the coupling takes place close to the transmit end of the system. FEXT 220 can be viewed as the coupling from the second twisted wire pair 142 to the first twisted wire pair 140, where the coupling takes place along the transmission path.

NEXT 210 and FEXT 220 can have different characteristics as a function of frequency, with FEXT 220 generally increasing as a function of frequency faster than NEXT 210. However, FEXT 220 is attenuated by the channel transfer function for first and second twisted wire pairs 140 and 142, and as a result NEXT 210 tends to be more detrimental than FEXT 220 in many xDSL systems. As shown in FIG. 2A, NEXT 210 and FEXT 220 can occur in both directions (upstream and downstream) of the xDSL system. While the discussion refers to the interaction of two twisted wire pairs in a bundle for simplicity, it will be understood that such NEXT and FEXT crosstalk interactions, as well as other forms of interference, can in principle occur between any two twisted wire pairs, and that a particular twisted wire pair can in fact be subject to interference from more than one other twisted wire pair simultaneously.

FIG. 2B illustrates an exemplary embodiment of the binder group 130 which can comprise a number of twisted wire pairs. each of which can be represented by a twisted wire pair identifier number as shown. The invention described herein can be utilized for any group of twisted wire pairs carrying xDSL signals. While binder groups typically contain 20-100 twisted wire pairs, the invention can be utilized on groups containing more or fewer twisted wire pairs.

The present invention can be applied to both ADSL systems for which standards have been developed, as well in VDSL or other DSL systems. In one embodiment. ADSL

transmission systems which are compliant with International Telecommunications Union standards are utilized for ATU-C and ATU-R. These modems comply with either the ITU G.992.1 Recommendation, or the ITU G.992.2 Draft Recommendation, both of which are incorporated herein by reference.

FIG. 3 illustrates a diagram for a tone or carrier subchannel allocation system 300 that can be used to realize the present invention. Tone or carrier subchannel allocation system 300 obtains measurements of the SNR in each tone or carrier subchannel using a Signal-to-Noise (or S/N) estimation entity 330. The tone or carrier subchannel allocation system 300 sends a tone or carrier subchannel signal denoted by number 335 to S/N estimation entity 330 and receives back a S/N measurement 338 for that tone signal. Systems complying with either of the G.922.1 or G.922.2 specifications can utilize a C-MEDLEY wideband pseudo-random signal to estimate the SNR. Other mechanisms can be used to determine the SNR in each tone or carrier subchannel and are well known to those skilled in the art.

Tone allocation system 300 also has access to service description records 320 which receive a request service level signal 329 and can return a guaranteed bit rate 327 and peak bit rate 325. The guaranteed bit rate 327 and peak bit rate 325 are indicative of the service level which has been contracted for by a subscriber, and can be used to assign tones to the modems (ATU-C 110 and ATU-R 160) used by that subscriber.

As shown in FIG. 3, tone or carrier subchannel allocation system 300 communicates with a tone or carrier subchannel rate and power control entity 310. Tone or carrier subchannel allocation system 300 calculates the payload which should be allocated and power which should be applied to each tone or carrier subchannel, and reports the tone or carrier subchannel 335, tone or carrier subchannel rate 318, and tone or carrier subchannel power 315 for that tone or carrier subchannel. Tone or carrier subchannel rate 318 is the number of bits that will be carried by tone or carrier subchannel 335, and is equivalent to the payload transported by tone or carrier

subchannel 335. In one embodiment, tone or carrier subchannel rate 318 varies from 1 to 15 bits.

FIG. 4 shows the block diagram of an embodiment of a computer system that can implement the twisted wire pair spectrum management system. A system bus 422 transports data amongst the CPU 203, the RAM 204, Read Only Memory – Basic Input Output System (ROM-BIOS) 406 and other components. The CPU 203 accesses a hard drive 400 through a disk controller 402. The standard input/output devices are connected to the system bus 422 through the I/O controller 201. A keyboard is attached to the I/O controller 201 through a keyboard port 416 and the monitor is connected through a monitor port 418. The serial port device uses a serial port 420 to communicate with the I/O controller 201. Expansion slots or connectors, such as Industry Standard Architecture (ISA) expansion slots 408 and Peripheral Component Interconnect (PCI) expansion slots 410 allow additional cards to be placed into or attached to the computer. In one embodiment, a network card is available to interface a local area, wide area, or other network.

FIGS. 5A and 5B illustrate the distribution of tones that is used in present standards based ADSL systems. As illustrated in FIG. 5A, downstream signals (ATU-C1 110 to ATU-R1 160 direction) are transmitted within a range of frequencies spanned by a frequency range defined from a downstream low frequency (f_{dl}) 500 to a downstream high frequency (f_{dh}) 510. For transmissions which are compliant with the ITU G.992.1 specifications two spectral masks are defined: the overlapped spectrum and the non-overlapped spectrum. In the former case, (f_{dl}) 500 is equal to 25.875 kHz and (f_{dh}) 510 is equal to 1.104 MHz. In the non-overlapped spectrum, upstream and downstream spectra are separated with the downstream spectrum ranging from 138 kHz ((f_{dl}) 500) to 1.104 MHz ((f_{dh}) 510). Alternately, and according to the ITU G.992.2 specifications, (f_{dl}) 500 is set to 25.875 kHz and (f_{dh}) 510 to 552 kHz in the

overlapped spectral masks. In the non-overlapped mode, (f_{dl}) 500 is equal to 138 kHz and (f_{dh}) 510 is equal to 552 kHz.

With respect to FIG. 5A, current standards compliant implementations allocate tones or carrier subchannels from the lower frequencies first and attempt to maximize the margin by maximizing the number of used tones or carrier subchannels and maximizing the power level of the used tones or carrier subchannels. This results in a worst case crosstalk environment.

Although power levels and corresponding spectral masks can be obtained from ITU standards, other spectral masks may be based on specifications from the Federal Communications Commission or other governmental agencies. These masks can be preprogrammed in the tone or carrier subchannel management system, or can be dynamically accessed by the tone or carrier subchannel management system from a server or other storage device. This feature allows for spectral masks to be dynamically changed by the tone or carrier subchannel management system.

As shown in FIG. 5B, upstream transmissions (ATU-R1 160 to ATU-C1 110 direction) are constrained by an upstream low frequency f_{ul} 520 and an upstream high frequency f_{uh} 530. In one ITU G.922.1 compliant embodiment f_{ul} 520 is equal to 25.875 kHz and f_{uh} 530 is equal to 138 kHz. The peak power spectrum distribution (PSD) is specified as –36.5 dBm/Hz in the downstream and –34.5 dBm/Hz in the upstream.

Although ADSL systems with a particular tone or carrier subchannel spacing have been described herein, the present invention can be applied to a variety of standardized and non-standardized xDSL systems including but without limitation to RADSL and VDSL systems. For VDSL systems the proposed masks define a low frequency limit of 120 kHz or 1.104 MHz and an upper frequency limit ranging from 10 to 30 MHz.

FIGS. 6A and 6B illustrate an exemplary allocation of tones or carrier subchannels according to the principles of the invention. The frequency spacing between tones is 4.3125

kHz, with a tolerance of +/- 50 ppm, although the present invention is not constrained by a particular tone or carrier subchannel spacing or width. Instead of allocating payload to all of the tones or carrier subchannels in the downstream and upstream frequency ranges, tones or carrier subchannels for downstream transmissions are selected beginning with f_{dh} 510, as shown in FIG. 6A. In the upstream direction tone or carrier subchannel allocation begins with f_{uh} 530, as shown in FIG. 6B. Only those tones or carrier subchannels required to fulfill the payload requirements are selected, as will be described. Depending on the payload required to be transported, the downstream lower frequency f_{dl} 500 and upstream lower frequency f_{ul} 520 may or may not be reached, unlike present systems which maximize the signal to noise margin on each tone or carrier subchannel and can use many more tones or carrier subchannels than are actually required to maintain an acceptable signal to noise margin.

In general, the frequencies of the individual carrier subchannels that comprise the subset are selected with regard to their relationship to a highest frequency end and a lowest frequency end of a subset of carrier subchannels. The subset of carrier subchannels is determined from a plurality of carrier subchannels. At least one of the carrier subchannels of the subset is capable of carrying at least one bit of a digital signal.

In the situation that there is a first range of frequencies that uses higher frequencies than those used in a second range of frequencies, there are four possible combinations of carrier subchannels in the frequency ranges that can be used. In one embodiment, the first transceiver uses carrier subchannels at the higher frequency end of the first, higher frequency range, and the second transceiver uses carrier subchannels at the higher frequency end of the second. lower frequency range. This embodiment provides the advantages of reducing far end crosstalk in both directions, and also reducing echo in both directions. This is exemplified in FIGs. 6A and 6B.

In another embodiment, illustrated by FIGs. 6C and 6D below, the first transceiver uses carrier subchannels at the higher frequency end of the first, higher frequency range, and the

second transceiver uses carrier subchannels at the lower frequency end of the second, lower frequency range. This embodiment provides maximal separation of the carrier subchannels. This embodiment provides the advantages of reducing near end crosstalk in both directions, reducing echo in both directions, and reducing far end crosstalk at the transceiver that transmits at the lower end of the lower frequency range.

In still another embodiment, not shown, the first transceiver uses carrier subchannels at the lower frequency end of the first, higher frequency range, and the second transceiver uses carrier subchannels at the lower frequency end of the second, lower frequency range. This embodiment provides the advantages of reducing near end crosstalk in transmissions from the second transceiver to the first transceiver, and also reducing echo in both directions.

In yet another embodiment, not shown, the first transceiver uses carrier subchannels at the lower frequency end of the first, higher frequency range, and the second transceiver uses carrier subchannels at the higher frequency end of the second, lower frequency range. This embodiment provides the advantage of reducing far end crosstalk in transmission from the second transceiver to the second transceiver,

In one embodiment, the bit error rate (BER) is specified to be equal to or less than one erroneous bit in 10^7 transmitted bits, which is alternatively expressed as a rate of 10^{-7}. A S/N margin of 4-6 dB is utilized, which includes a coding gain of approximately 3 dB. As an example, for a 16 Quadrature Amplitude Modulation (QAM) signal the required SNR for a BER of 10^{-7} is 21.3 dB, assuming uncoded data. With a coding gain of 3 dB a SNR in the range of 22.3 – 24.3 dB would be considered to be adequate.

FIGS. 6C and 6D illustrate an embodiment of the invention in which tones or carrier subchannels in the downstream are selected beginning with f_{dh} 510, as shown in FIG. 6C. while tones or carrier subchannels in the upstream frequency range are selected beginning with f_{ul} 520 as shown in FIG. 6D. The advantage of this embodiment is that maximum frequency separation

of the upstream and downstream signals is achieved while simultaneously applying the high frequency tone or carrier subchannel allocation scheme to the downstream band.

FIGS. 7A and 7B illustrate another feature of the present invention, in which the power in each tone or carrier subchannel is limited to a power which maintains a minimum SNR margin. FIG. 7A illustrates the results of tone or carrier subchannel allocation and tone or carrier subchannel power control according to this method, wherein higher frequency tones or carrier subchannels which are subject to higher losses have higher powers in order to maintain the minimum SNR, and where lower frequency tones or carrier subchannels have lower powers. As shown in FIG. 7B, tone or carrier subchannel powers are controlled in the same way in the upstream direction, with higher powers typically being applied to tones at higher frequencies. In the event that there is significant interference present in a particular tone, that tone or carrier subchannel may require a higher power than other tones or carrier subchannels, or in the event of a very high level of interference the tone or carrier subchannel may not be useable at all.

FIGS. 7C and 7D illustrate an embodiment of the invention in which tones of varying power levels in the downstream are selected beginning with f_{dh} 510, as shown in FIG. 7C, while tones of varying power in the upstream frequency range are selected beginning with f_{ul} 520 as shown in FIG. 7D. As discussed with respect to FIGS. 6C and 6D, the advantage of this embodiment is that maximum frequency separation of the upstream and downstream signals is achieved while simultaneously applying the high frequency tone or carrier subchannel allocation scheme to the downstream band.

The present invention allows for the reduction of power in tones or carrier subchannels where the signal to noise margin is much higher than required to maintain an acceptable BER with an adequate margin. A signal to noise margin above 6 dB can be considered to be "excessive" in the sense that the excess power utilized could cause interference with other

signals. Reducing the power to maintain a signal to noise margin in the range of 4-6 dB will reduce interference problems.

In one embodiment, power can be reduced in increments of 1 –3 dB. A coarse power adjustment followed by a fine power adjustment can be utilized. A typical starting power for ATU-R1 160 would be –38 dBm/Hz, while at ATU-C1 110 a typical starting power would be –40 dBm/Hz. Power can be reduced to obtain a sufficient but not excessive signal to noise margin.

In addition to the problems associated with crosstalk in systems where the central office side modems are all in the same location, a particular problem, called the "near-far problem," arises when the second modem channel bank 105 is located much closer to a group of subscribers, and shares a binder group 130 with twisted wire pairs served by the first modem channel bank 100. The near-far problem results from the fact that modems close to the subscribers may transmit at a high power with respect to the power which is actually needed to transmit a signal to the intended recipient. Present ADSL standards permit modems to operate at the maximum allowable power, with the excess power simply assuring a higher SNR margin at the receiver. Such transmissions, while assuring a high SNR margin at the corresponding receivers. also present significant interference on twisted wire pairs carrying signals from a central office located far from the subscriber.

The present invention provides a solution to the near-far problem by insuring that modems only utilize the tones or carrier subchannels required, beginning at a specified high frequency tone or carrier subchannel, and do not transmit power in excess of what is required to maintain an acceptable SNR margin.

In one embodiment. the power of a carrier subchannel changes with its position in the frequency spectrum of its subset. a carrier subchannel of lower frequency being operated at lower power, for example because. in general, lower frequency signals suffer less attenuation per unit distance than higher frequency signals.

In another embodiment that combines the features of wide separation in frequency between the upstream and downstream communication channels. and also takes into consideration the general tendency for lower frequency signals to lose less power to radiation than higher frequency signals, the separation of the carrier subchannels in frequency spectrum can be combined with control of power (by control of gain) in each carrier subchannel to reduce the excess power that is used in conventional systems, and to reduce crosstalk.

Additionally, one can understand that it is possible to reduce the gain for any carrier subchannel that does not have to carry as many bits as the maximum number of bits that it is capable of carrying. In the case that a carrier subchannel is not required to carry any bits in order to transmit the data, the transmission gain of such an unused carrier subchannel is set to zero.

FIGs. 8A and 8B illustrate a flowchart for the allocation of tones according to the present invention and based on the use of tone or carrier subchannel allocation system 300. Although the principles of the invention can be implemented in an object oriented programming language, the flowchart shown in FIGs. 8A and 8B can be used to better understand the method and steps used to allocate tones or carrier subchannels.

Turning to FIG.8A, beginning from a start step 810 the system determines the guaranteed bit rate 820. This step can be performed using the service description records 702 that returns the guaranteed bit rate 327. The power spectrum distribution (PSD) mask to be used on the xDSL line is retrieved at retrieve PSD mask step 825. The PSD mask can be any standardized, non-standardized or government mandated PSD mask.

Under certain conditions it is advantageous to use a PSD mask which sets the nominal power for tones at a level which is substantially below what is permitted. As an example, a nominal (coarse) power mask of –50 dBm/Hz may be used. More tones will be utilized than if the power mask is set at –40 dBm/Hz, but the decreased power will result in decrease of the modem contribution to NEXT 110 and FEXT 220 by 10 dB.

In an alternate embodiment the PSD mask is determined based on measurements made by tone or carrier subchannel allocation system 300. A collection of estimates of the distances between the ATU-C and the ATU-R as determined from measurements of SNR are used to determine a value for the nominal power mask. The power mask can be uniform across the downstream channel or upstream channel, of can vary from tone or carrier subchannel to tone or carrier subchannel.

The next step is to determine within the constraints of the PSD mask the highest frequency tone or carrier subchannel, which will provide an acceptable SNR. This is referred to as the Maximum Usable Frequency (MUF) and is used to determine MUF(N_{max}) in a determine MUF(N_{max}) step 830. The MUF can be determined by making measurements of the SNR for each tone or carrier subchannel and determining which tone or carrier subchannel has a SNR which permits the minimum payload, that is, at least one bit (typically measured in terms of bits/tone), to be carried with an acceptable S/N margin. The highest frequency tone or carrier subchannel which carries the minimum payload with the minimum SNR is MUF(N_{max}), where N_{max} is the carrier subchannel number, counting from the low frequency end of the range of frequencies.

Once the highest tone or carrier subchannel which can be utilized has been determined, payload is allocated to that tone or carrier subchannel in an allocate payload in tone or carrier subchannel N step 840. The tone or carrier subchannel number N is decremented in a decrement N by one step 850, and a test is performed to determine if the payload corresponding to the guaranteed bit rate has been allocated. This test is performed in a payload allocation test 860. If the payload has not been fully allocated, the system returns to the allocate payload in tone or carrier subchannel N step 840 and continues by allocating payload to that tone or carrier subchannel. Once the payload has been fully allocated. as determined by the payload allocation step 860, the payload of the last tone or carrier subchannel is determined.

As shown in FIG.8B, at the "last tone or carrier subchannel payload too low" step 865, the system determines if the payload allocated to the last tone or carrier subchannel is lower than a certain limit determined by the system, in which case the system proceeds to the next step. If the number of bits assigned to that tone or carrier subchannel is acceptable, the procedure ends in an end step 870.

The number of bits assigned to the last tone or carrier subchannel can be such that transmitting that tone or carrier subchannel would result in an inefficient use of bandwidth. This determination is made at reallocate last tone or carrier subchannel payload step 875. At this step the system can decide to conserve the last tone or carrier subchannel with its payload. which will result in a low transmit power for that tone or carrier subchannel. This option ends the procedure at end step 870. The YES option of reallocate last tone or carrier subchannel payload step 875 leads to a payload reallocation step 880. In this step, the number of bits assigned to the last tone or carrier subchannel are redistributed among the already filled tones or carrier subchannels. This redistribution can be done randomly or in a more structured manner beginning from the tone or carrier subchannel immediately above the said last tone or carrier subchannel to the higher tones or carrier subchannels. Redistribution of these bits may require increasing fine tone or carrier subchannel power levels.

In another embodiment, the redistribution can be done from tone or carrier subchannel N_{max} downward. At reallocation convergent step 885, a test is performed on the payload reallocation procedure carried on step 880. If the payload allocation performed at step 840 is such that the payload of the tones can not be increased, the payload reallocation procedure will diverge, in which case, the system conserves the first payload map obtained at the output of the loop composed by steps 840, 850 and 860, and ends the procedure at end step 870.

If the reallocation procedure is convergent, the first payload map is replaced with the new payload map obtained from payload reallocation step 880 and the procedure exits at end step 870.

FIG. 9 illustrates a flowchart for the allocation of tones and control of power. In this process, tones are initially selected at the maximum allowed power level in steps identical to those described with respect to FIG. 8A. The maximum acceptable power may be determined from a spectral mask or from a calculation used to determine a nominal power mask for that tone or carrier subchannel or set of tones or carrier subchannels. The process proceeds to a SNR margin exceeded test 900 at which point a determination is made as to whether the SNR margin has been exceeded, in which case the power in that tone or carrier subchannel can be lowered. The power in the tone or carrier subchannel is lowered in a decrease power step 910. The SNR margin exceeded test 900 is performed again to determine if the power in the tone or carrier subchannel is acceptable. The power can be decreased repeatedly by cycling through the SNR margin exceeded test 900 and the decrease power step 910, until a suitable level of power is reached. After the power level is acceptable, counter N is decremented in a decrement N step 850 and the payload allocated test 860 is performed. If there is additional payload to be allocated to tones the system returns to allocate payload in tone or carrier subchannel N step 840. After the payload is allocated in the tones, the process proceeds to an end step 870.

Thus, it is evident that there has been provided in accordance with the present invention a multicarrier communication technique that fully satisfies the aims and objections, and achieves the advantages described above.

Although this invention has been illustrated by reference to specific embodiments, it will be apparent to those skilled in the art that various changes and modifications may be made which clearly fall within the scope of the invention. Accordingly, the present invention is to be viewed

quite broadly as encompassing all such alternatives, modifications, and variations as are within the spirit and scope of the hereinafter appended claims.

What is claimed is:

CLAIMS

1. In a communications system including a plurality of transceivers communicating with each other, a multicarrier data modulation method for reducing the effect of interference phenomena , the method comprising:

providing a plurality of carrier subchannels for use in modulating digital signals of an input data stream;

determining a subset of the plurality of carrier subchannels, the subset spanning a range of frequencies having a highest frequency end and a lowest frequency end, each carrier subchannel of the subset being capable of carrying at least one bit of the digital signals; and

allocating at least one of the carrier subchannels of the subset for transmitting one or more bits of the digital signals, wherein every allocated carrier subchannel of the subset is at one of the ends of the frequency range so as to reduce the effect of an interference phenomenon .

2. The method of claim 1 wherein the allocating of the carrier subchannels uses fewer than all of the carrier subchannels in the subset.

3. The method of claim 1, further comprising the step of carrying fewer bits in at least one carrier subchannel in the subset than that carrier subchannel is capable of carrying.

4. The method of claim 1 wherein the range of frequencies in the subset of carrier subchannels includes at least one carrier subchannel that is incapable of carrying at least one bit.

5. The method of claim 1 further comprising:

modulating digital signals communicated from a first transceiver to a second transceiver using a first range of frequencies, the first range of frequencies allocated from a first subset of the plurality of carrier subchannels; and

modulating digital signals communicated from the second transceiver to the first transceiver using a second range of frequencies, the second range of frequencies allocated from a

second subset of the plurality of carrier subchannels different from the first subset of the plurality of carrier subchannels.

6. The method of claim 1, further comprising the step of adjusting a gain of at least one carrier subchannel in the subset to reduce the number of bits that the carrier subchannel can carry from a maximum number of bits to a lesser number of bits that is sufficient to carry the information present in a digital signal.

7. The method of claim 1 wherein the interference phenomenon is at least one of a near end crosstalk, a far end crosstalk, a noise, and an echo.

8. The method of claim 1, further comprising the step of determining a maximum number of bits of a digital signal that each carrier subchannel of the subset can carry to provide a predetermined quality of service.

9. The method of claim 8, further comprising the step of determining the predetermined quality of service based on at least one of a bit transmission rate, a bit error rate, a signal-to-noise ratio margin, and a power.

10. In a communications system including a plurality of transceivers communicating with each other, a multicarrier data modulation apparatus that reduces the effect of interference phenomena , the apparatus comprising:

a module capable of modulating digital signals of an input data stream on to a plurality of carrier subchannels;

a subchannel selection module that selects a subset of the plurality of carrier subchannels, the subset spanning a range of frequencies having a highest frequency end and a lowest frequency end, each carrier subchannel of the subset being capable of carrying at least one bit of the digital signals; and

a carrier subchannel allocation module that allocates at least one of the carrier subchannels of the subset for transmitting one or more bits of the digital signals, wherein every

allocated carrier subchannel of the subset is at one of the ends of the frequency range so as to reduce the effect of an interference phenomenon.

11. The apparatus of claim 10 wherein the digital signal modulation module uses fewer than all of the carrier subchannels in the subset.

12. The apparatus of claim 10 wherein the subset of carrier subchannels spans a range of frequencies that includes at least one carrier subchannel that is incapable of carrying at least one bit.

13. The apparatus of claim 10, further comprising a module that receives a transmitted digital signal that has been modulated on to one or more carrier subchannels.

14. The apparatus of claim 13 wherein transmitted digital signals are modulated with a first range of frequencies, the first range of frequencies allocated from a first subset of the plurality of carrier subchannels, and received digital signals are modulated with a second range of frequencies, the second range of frequencies allocated from a second subset of the plurality of carrier subchannels different from the first subset of the plurality of carrier subchannels.

15. The apparatus of claim 10, further comprising a gain control module that controls a gain of at least one carrier subchannel in the subset to reduce a number of bits that the carrier subchannel can carry from a maximum number of bits to a lesser number of bits sufficient to carry the information present in a digital signal.

16. The apparatus of claim 15 wherein the gain control module controls the gain such that the lesser number of bits is a minimum number of bits necessary to carry the information present in the digital signal.

17. The apparatus of claim 10, further comprising an interference detection module that determines a maximum number of bits of a digital signal that each carrier subchannel of the subset can carry to provide a predetermined quality of service.

18. The apparatus of claim 17 wherein the interference detection module detects at least one of a bit transmission rate. a bit error rate. a signal-to-noise ratio margin. a power. a near end crosstalk, a far end crosstalk, a noise level, and an echo.

19. In a communications system including a plurality of transceivers communicating with each other, a multicarrier data modulation apparatus that reduces the effect of interference phenomena , the apparatus comprising:

a module that receives a transmitted digital signal that has been modulated on to one or more carrier subchannels, the one or more carrier subchannels comprising a subset of carrier subchannels allocated from a plurality of carrier subchannels, the subset spanning a range of frequencies having a highest frequency end and a lowest frequency end, at least one of the carrier subchannels of the subset being capable of carrying at least one bit of the digital signals, wherein every allocated carrier subchannel of the subset is at one of the ends of the frequency range so as to reduce the effect of an interference phenomenon; and

a demodulator module that demodulates the transmitted digital signal that has been modulated on to one or more carrier subchannels, and that creates from the demodulated transmitted digital signal an output data stream.

20. A computer program recorded on a machine-readable medium. the computer program when executing on a computer performing the steps of:

determining a subset of a plurality of carrier subchannels, the subset spanning a range of frequencies having a highest frequency end and a lowest frequency end. each carrier subchannel of the subset being capable of carrying at least one bit of the digital signals; and

allocating at least one of the carrier subchannels of the subset for transmitting one or more bits of the digital signals, every allocated carrier subchannel of the subset being at one of the ends of the frequency range so as to reduce the effect of an interference phenomenon.

21. The computer program of claim 20, the computer program when executing on a computer performing the step of determining a maximum number of bits of a digital signal that a carrier subchannel can carry to provide a predetermined quality of service.

22. The computer program of claim 21, the computer program when executing on a computer performing the step of modulating the digital signal with a first carrier subchannel having a first frequency using the maximum number of bits that the first carrier subchannel can carry before modulating the digital signal with a second carrier subchannel having a second frequency.

23. The computer program of claim 21, the computer program when executing on a computer performing the step of:

calculating a reduced number of bits that the carrier subchannel carries from the maximum number of bits that the carrier subchannel can carry to a lesser number of bits sufficient to carry the information present in a digital signal.

24. The computer program of claim 23, the computer program when executing on a computer performing the step of modulating the digital signal with the carrier subchannel using the lesser number of bits in place of the maximum number of bits.